# Baseband Recording and Playback

S. S. Kent

Radio Frequency and Microwave Subsystems Section

J. I. Molinder

Tracking and Data Acquisition Engineering Section

*Analog recordings of spacecraft telemetry signals are made by Deep Space Network Deep Space Stations to provide backup for both spacecraft and ground station anomalies. In this article the requirements that must be met to insure successful baseband recording and playback are given. Recording and playback procedures are developed to insure that these requirements are met and performance results from tests conducted at the Compatibility Test Area (JPL) are tabulated.*

## I. Introduction

Analog recordings of spacecraft telemetry signals are made by Deep Space Network Deep Space Stations to provide backup for both spacecraft and ground station anomalies. These recordings can be made at various points along the telemetry string as shown in Fig. 1. Both the effectiveness of the backup provided and the recording bandwidth required increase as the recording point moves upstream (toward the antenna). For example, an unanticipated change in spacecraft subcarrier frequency or data rate will cause the Subcarrier Demodulator Assembly (SDA) to lose lock. If this happens, no data can be recovered unless the recording is made upstream of the SDA. In addition, recording upstream of the SDA provides a backup in the event of a ground station failure or operator error affecting the SDA or other equipment further downstream. On the other hand, the recording bandwidth required just upstream of the SDA (baseband) is greater than that

required just downstream of the SDA (SDA output) by a factor of approximately the ratio of the spacecraft subcarrier frequency to half the data symbol rate. This ratio can easily be greater than ten. An even larger factor may result in the case of more than one subcarrier on a single carrier. Open-loop recording (Fig. 1) provides further backup since the receiver does not have to be in lock (as required for baseband recording) but increases the required recording bandwidth by a factor of two (the ratio of IF to baseband bandwidth) over that needed for baseband recording.

In this article the requirements that must be met to insure successful baseband recording and playback are given. Recording and playback procedures are developed to insure that these requirements are met and performance results from tests conducted at CTA 21 are tabulated.

## II. Spectrum of Baseband Signal (Ref. 1)

The baseband signal $b(t)$ is given by

$$b(t) = Kd(t)s(t)$$

where

$s(t)$ = square wave subcarrier of unit amplitude and fundamental frequency $f_{sc}$

$d(t)$ = binary data waveform taking on the values of $-1$ and $1$ with symbol rate $f_d$ depending on whether the data symbol is 1 or 0 respectively

and

$K$ = constant

Expanding $s(t)$ in a Fourier series (and without loss of generality choosing the reference such that $s(t)$ is even) yields

$$b(t) = Kd(t) \sum_{n=1}^{\infty} a_n \cos n2\pi f_{sc} t$$

where

$$a_n = \frac{4}{\pi n} \sin \frac{n\pi}{2} = \begin{cases} (-1)^{\frac{n-1}{2}} \dfrac{4}{n\pi} & n \text{ odd} \\ 0 & n \text{ even} \end{cases}$$

Thus the baseband spectrum consists of the data spectrum centered on the odd harmonics of the square-wave subcarrier.

## III. Degradation Due to Loss of Subcarrier and Data Harmonics (Ref. 1)

Since $d(t)s(t)$ takes on only the values $\pm 1$, the available power in the baseband signal is $K^2$. However, since the bandwidth of this signal is infinite, only a finite number of sidebands are actually preserved. The available power if subcarrier harmonics above the $N$th are filtered out (assuming the data spectrums around the $N$ harmonics are preserved, i.e., data rate is low compared to subcarrier frequency) is given by

$$P_N = K^2 \frac{8}{\pi^2} \sum_{\substack{n=1 \\ (n \text{ odd})}}^{N} \frac{1}{n^2}$$

and thus the degradation in dB is

$$\rho_{dB} = 10 \log_{10} \frac{P_N}{K^2} = 10 \log_{10} \frac{8}{\pi^2} \sum_{\substack{n=1 \\ (n \text{ odd})}}^{N} \frac{1}{n^2}$$

Values of $\rho_{dB}$ versus $N$ are given in Table 1.

When the data rate is not small compared to the subcarrier frequency, additional degradation occurs due to loss of data sidebands around the subcarrier harmonic near the edge of the system passband. The amount of degradation can be approximated by assuming a symbol stream of alternating 1's and 0's (yielding the largest possible data bandwidth produced by a square wave of fundamental frequency $f_d/2$) and assuming only a finite number of upper data sidebands on the highest subcarrier harmonic are preserved (all the lower sidebands are assumed to be preserved). Under these assumptions the baseband signal $b(t)$ can be written

$$b(t) = Kd(t) \sum_{n=1}^{N-2} a_n \cos n2\pi f_{sc} t + K \left[ a_N \cos N2\pi f_{sc} t \sum_{j=1}^{\infty} a_j \cos j\pi f_d t \right]^J$$

where

$N$ = highest subcarrier harmonic preserved

$$a_j = \frac{4}{\pi j} \sin \frac{j\pi}{2} = \begin{cases} (-1)^{\frac{j-1}{2}} \dfrac{4}{\pi j} & j_{\text{odd}} \\ 0 & j_{\text{even}} \end{cases}$$

$[\ ]^J$ = indicates that all data sidebands up to and including the $J$th upper sideband are preserved.

The available power is given by

$$P_{N,J} \cong K^2 \frac{8}{\pi^2} \sum_{\substack{n=1 \\ (n \text{ odd})}}^{N-2} \frac{1}{n^2} + K^2 \frac{8}{\pi^2 N^2} \left( 0.5 + \frac{4}{\pi^2} \sum_{\substack{j=1 \\ (j_{\text{odd}})}}^{J} \frac{1}{j^2} \right)$$

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and thus

$$\rho_{dB} = 10 \log_{10} \frac{P_{N,J}}{K^2}$$

$$= 10 \log_{10} \frac{8}{\pi^2} \left[ \sum_{\substack{n=1 \\ (n \text{ odd})}}^{N-2} \frac{1}{n^2} + \frac{1}{N^2} \left( 0.5 + \frac{4}{\pi^2} \sum_{\substack{j=1 \\ (j_{\text{odd}})}}^{J} \frac{1}{j^2} \right) \right]$$

Values of $\rho_{dB}$ versus $N$ and $J$ are given in Table 2.

## IV. Recorder Bandwidth and Phase Linearity Limitations

In general the tape recorder bandwidth is directly proportional to tape speed. For example, the Ampex FR 2000A and Honeywell 96 recorders have bandwidths of 500 kHz at 76.2 cm/s (30 ips), 1 MHz at 152.4 cm/s (60 ips), and 2 MHz at 304.8 cm/s (120 ips). Thus it is apparent that a tradeoff exists between data degradation and tape usage (at 304.8 cm/s (120 ips) a reel of tape lasts approximately 15 minutes).

In addition, because of the coherent detection process used in the DSN it is important to preserve the phase relationship of the subcarrier and data components. Derivation of degradation due to phase nonlinearities is given in Ref. 2. In selecting an appropriate speed, both the amplitude and phase response of the recorder as a function of tape speed must be considered.

## V. Requirements to Minimize Degradation for a Given Recorder Bandwidth

The following requirements must be met to minimize degradation in the baseband recording and playback process for a given recorder bandwidth.

(1) Linear operation and proper phasing of the receiver telemetry channel.

(2) Linear operation of the recorder in both the record and playback modes.

(3) Proper input levels to the Subcarrier Demodulator Assembly (SDA).

(4) Sufficiently small variations in tape velocity to insure proper operation of downstream equipment requiring phase lock.

A recording and playback procedure to insure that these requirements are met is developed in the next section.

## VI. Procedure

The development of the portion of the procedure to meet each requirement is given below. At the end of the section the overall procedure is summarized.

### A. Requirement 1

The Block III receiver telemetry channel IF and video amplifiers are designed for maximum output levels of +6 dBm (sine, 50 Ω) and +10 dBm (sine, 50 Ω) respectively. Since, for equal rms levels, a noise waveform has 3 dB higher amplitude peaks (using a 95% of the peaks criteria) than does a sine wave, the output levels of the IF and video amplifiers should not exceed +3 and +7 dBm, respectively. Levels of 0 and +5 dBm are specified in the procedure to allow some safety margin.

The Block IV receiver telemetry channel uses an internal AGC to maintain linearity at an output level of approximately +10 dBm (50 Ω), and thus no adjustment is required.

Correct phasing of the phase detector in either the Block III or Block IV receivers must be insured by following the standard phasing procedures for the receiver. The Block III receiver must be rephased each time the telemetry bandwidth is changed, while the Block IV receiver has separate phase adjustments for each bandwidth and requires only one initial adjustment.

### B. Requirement 2

Standard procedures for calibrating the analog recorder use a 1-V rms sine wave input (+13 dBm, 50 Ω). The record electronics are adjusted for 1% third harmonic distortion with this input. A +5-dBm (noise) input is specified in the procedure to insure the input level is well within the linear range of the recorder.

### C. Requirement 3

The Block III and Block IV SDAs are designed to operate with signal levels of -75 dBm and -70 dBm, respectively, at the output of the modulation index (step) attenuator. With the attenuator set at 0, this corresponds to a "tape input" signal level of -29 dBm and -28 dBm for the Block III and Block IV SDAs, respectively. An input level of -28 dBm is selected as a standard. In addition, the total input (signal + noise) must not exceed ±1.4 peak (+10 dBm noise into 50 Ω). Note that this means the minimum signal-to-noise ratio, $S/N = -28 - 10 = -38$ dB.

Given the value of $ST_b/N_o$ in dB the signal-to-noise ratio out of the recorder can be determined by observing that

$$\frac{S}{N} = \frac{S}{N_o W} = \frac{ST_b}{N_b} \times \frac{1}{T_o W} = \frac{ST_b}{N_o} \times \frac{f_d}{W}$$

and thus,

$$\left(\frac{S}{N}\right)_{dB} = \left(\frac{ST_b}{N_o}\right)_{dB} + 10 \log_{10} f_d - 10 \log_{10} W$$

where $f_d = 1/T_b$ = data rate and $W$ is either the telemetry noise bandwidth or twice the recorder noise bandwidth, whichever is smaller.

Denote the output level of the recorder in dBm as $R_o = S + N$. Thus,

$$\frac{S}{R_o} = \frac{S}{S + N} = \frac{S/N}{S/N + 1}$$

Solving for $S$ yields

$$S = \frac{R_o \times S/N}{S/N + 1}$$

For most cases of interest

$$\frac{S}{N} \ll 1$$

and thus

$$S \cong R_o \times \frac{S}{N}$$

or in dBm

$$S = R_o + \left(\frac{S}{N}\right)_{dB}$$

The attenuator setting $A$ necessary to reduce this level to the required value of $-28$ dBm can be determined by observing that

$$S - A = -28 \text{ dBm}$$

or, in dB

$$A = S + 28 = R_o + \left(\frac{S}{N}\right)_{dB} + 28$$

## D. Requirement 4

A theoretical analysis of the effect of tape velocity errors on the operation of downstream equipment requiring phase lock (the SDA and SSA) is difficult and has not been attempted. Experience gained from tests at CTA 21 show that current generation instrumentation recorders (specifically the Ampex FR 2000A and Honeywell 96) have sufficiently low tape velocity variations to permit playback at signal-to-noise ratios approaching telemetry system threshold conditions. This is not true of older-generation recorders (such as the Ampex FR 1400 for example).

The recording and playback procedures can be summarized as follows:

### 1. Recording

(1) Phase the telemetry string at the required telemetry bandwidth setting.

(2) (Block III receiver only) With no signal applied to the receiver, set the manual gain control (MGC) to correspond to the predicted carrier level (for strong signal conditions the actual receiver input signal-to-noise ratio should be simulated). Using a true reading rms voltmeter terminated in 50 $\Omega$, adjust the IF attenuator for 0 dBm (50 $\Omega$) at the IF linear output port.

(3) (Block III receiver only) With the IF attenuator set as determined in step 2, adjust the video output for 5 dBm (50 $\Omega$) and connect to recorder input terminated in 50 $\Omega$.

(4) (Block IV receiver only) Attenuate the video output to a level of 5 dBm (50 $\Omega$) and connect to recorder input terminated in 50 $\Omega$.

### 2. Playback

(1) Using a true reading rms voltmeter terminated in 50 $\Omega$, measure the recorder reproduce output level in dBm. Call this level $R_o$.

(2) Let $W$ = either the telemetry noise bandwidth or twice the recorder bandwidth, whichever is smaller, and compute

$$\left(\frac{S}{N}\right)_{dB} = \left(\frac{ST_b}{N_o}\right)_{dB} + 10 \log_{10} f_d - 10 \log_{10} W$$

where $f_d$ is the bit rate.

(3) Insert attenuator between reproduce output and input to SDA balanced modulator and compute setting A in dB as follows:

$$A =_{dB} = R_o + \left(\frac{S}{N}\right)_{dB} + 28$$

Set the SDA step attenuator at 0 dB.

## 3. Test Procedures and Results

A series of baseband recording and playback tests using the above procedures were conducted at CTA 21 using the Block III receiver and the following test procedure (see Fig. 2).

(1) Phase the telemetry string at the required telemetry bandwidth setting using standard procedures.

(2) With the Simulation Conversion Assembly (SCA) set for the desired data, subcarrier and modulation index, adjust the attenuator of the test transmitter for the desired $ST_b/N_o$ using the $Y$-factor equipment.

(3) Record the bit error rate (BER) in the direct "10 MHz" configuration and determine $ST_b/N_o$ using the theoretical bit error rate curve (this also verifies the $Y$-factor setting of step 2).

(4) With the simulated data applied, adjust the IF attenuator for a level of 0 dBm (50 Ω) at the output of the receiver IF amplifier and adjust the junction box preceding the video amplifier for a level of 5 dBm (50 Ω) at the output of the video amplifier.

(5) Record the output of the video amplifier and simultaneously monitor the BER using the record and monitor configuration (output of the video amplifier properly attenuated and connected to the input of the SDA balanced modulator).

(6) Play back the data recorded in step 5 through an attenuator connected to the SDA balanced modulator input (playback configuration). Record the BER and determine $ST_b/N_o$ using the theoretical bit error rate curve.

The results of these tests are tabulated in Tables 3 and 4. The direct "10 MHz" configuration is the normal real-time telemetry path whereas in the record and monitor configuration one output of the receiver video amplifier (baseband subcarrier + data) is connected to the input of the SDA balanced modulator and another to the recorder input. Comparing the record and monitor with the playback column gives the degradation due to the recorder alone. In some cases, the record and monitor configuration gives a higher signal-to-noise ratio than the direct "10 MHz" configuration. The probable cause is phase misalignment in the real-time (direct "10 MHz") path but this has not been verified. It should also be pointed out that the degradation is a function of signal-to-noise ratio with higher degradations expected at higher signal-to-noise ratios where the noise added by the recorder (both amplitude and phase) is a larger fraction of the total system noise.

## V. Conclusions

A procedure to insure successful baseband recording and playback at signal-to-noise ratios $(ST_b/N_o)$ approaching the threshold of the telemetry system has been developed. This procedure has been verified by extensive testing at CTA 21 and has been used for successful on-site playback of baseband recordings made during the Viking mission (Refs. 3-6; see also the article by G. Hamilton in this issue.) Theoretical analyses of the approximate data degradation due to limitations in bandwidth and phase linearity have been made. Since the tape recorder bandwidth is directly proportional to tape speed, a tradeoff must be made between allowable degradation and tape usage. This tradeoff is complicated by the fact that very little information on the recorder phase response is currently available, although some data have been derived from pulse response tests. Since the signal-to-noise ratio of the recorder is normally much higher (>20 dB) than the signal-to-noise ratio of the data typically recorded, it is believed that practically all of the data degradation is now due to limitations in bandwidth and phase linearity.

# Acknowledgments

# References

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**Table 1. Theoretical degradation versus highest subcarrier harmonic (N) preserved**

| N | $\rho_{dB}$ |
|---|---|
| 1 | −0.91 |
| 3 | −0.45 |
| 5 | −0.30 |
| 7 | −0.22 |
| 9 | −0.18 |

**Table 2. Theoretical degradation versus highest subcarrier harmonic (N) and highest square-wave upper data harmonic (J) preserved**

| N | J | $\rho_{dB}$ |
|---|---|---|
| 1 | 1 | −1.34 |
| 1 | 3 | −1.13 |
| 1 | 5 | −1.06 |
| 3 | 1 | −0.50 |

**Table 3. CTA 21 Baseband recording and playback tests (Ampex FR 20002 A)**

| Date | Data rate | Subcarrier frequency | Tape speed, cm/s (in./s) | SNR ($ST_b/N_o$ or $ST_s/N_o$), dB | | | Degradation, dB | |
|---|---|---|---|---|---|---|---|---|
| | | | | Direct "10 MHz" | Record and Monitor Direct (TLM) | Playback | Total | Recorder |
| 11-11-75 | 16 kbits/s (32,6)[1] | 240 kHz | 76.2 (30) | | 2.4 | 0.85 | | 1.55 |
| | | | | 4.15 | 3.9 | 2.75 | 1.4 | 1.15 |
| | | | | | 5.55 | 3.65 | | 1.9 |
| | | | 152.4 (60) | | 3.75 | 3.15 | | 0.6 |
| | | | 304.8 (120) | | 3.75 | 3.45 | | 0.3 |
| 9-23-75 | 16 kbits/s (32,6) | 240 kHz | 76.2 (30) | 3.45 | 3.75 | 2.7 | | 1.05 |
| | | | 152.4 (60) | | 3.75 | 1.75 | | 2.0 |
| | | | 304.8 (120) | | 3.8 | 2.7 | | 1.1 |
| 8-7-75 | 64 bits/s (UC) | 25.6 kHz | 76.2 (30) | 3.9 | 3.2 | 2.45 | 1.45 | 0.75 |
| 8-7-75 | 2048 bits/s (UC) | 26.624 kHz | 76.2 (30) | 5.2 | 4.4 | 3.8 | 1.4 | 0.6 |
| 7-31-75 | 2048 bits/s (UC) | 26.624 kHz | 76.2 (30) | 3.9 | 3.3 | 2.25 | 1.65 | 1.05 |
| 7-28-75 | 64 bits/s (UC) | 25.6 kHz | 76.2 (30) | 3.9 | 2.5 | 1.1 | 2.8 | 1.4 |
| 7-28-75 | 64 bits/s (UC) | 102.4 kHz | 76.2 (30) | | 2.9 | 1.7 | | 1.2 |
| 7-9-75 | 64 bits/s (UC) | 25.6 kHz | 76.2 (30) | 3.65 | 2.65 | 0.7 | 2.95 | 1.95 |
| 7-9-75 | 16 kbits/s (UC) | 240 kHz | 152.4 (60) | 5.4 | 4.95 | 4.5 | 0.9 | 0.45 |
| 7-8-75 | 64 bits/s (UC) | 25.6 kHz | 76.2 (30) | | 3.0 | 1.05 | | 1.95 |

[1](32,6) Block coded   UC = Uncoded

**Table 4. CTA 21 baseband recording and playback tests (Honeywell 96)**

| Date | Data rate | Subcarrier frequency, kHz | Tape speed, cm/s (in./s) | SNR ($ST_b/N_o$ or $ST_s/N_o$), dB | | | Degradation, dB | |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| | | | | Direct "10 MHz" | Record and Monitor | Playback | Total | Recorder only |
| 2-24-76 | 16 kbits/s (32,6)[1] | 240 | 304.8 (120) | | 4.5 | 4.1 | | 0.4 |
| | | | 152.4 (60) | | 5.0 | 4.55 | | 0.45 |
| | | | 152.4 (60) | | 2.9 | 2.45 | | 0.45 |
| | | | 76.2 (30) | | 5 | 3.45 | | 1.55 |
| 3-2-76 | 16 kbits/s (32,6) | 240 | 152.4 (60) | | 4.25 | 3.45-3.75 | | 0.8-0.5 |
| | | | 76.2 (30) | | 4.25 | 3.05 | | 1.2 |
| | | | 76.2 (30) | | 4.3 | 2.95-3.15 | | 1.35-1.15 |
| 3-23-76 | 16 kbits/s (32,6) | 240 | 152.4 (60) | | 4.35 | 4.05 | | 0.3 |
| | | 360 | 152.4 (60) | | 4.3 | 3.65 | | 0.65 |
| | 33-1/3 bits/s (UC) | 24 | 38.1 (15) | | 6.75 | 5.85 | | 0.9 |

[1](32,6) Block coded   UC = Uncoded
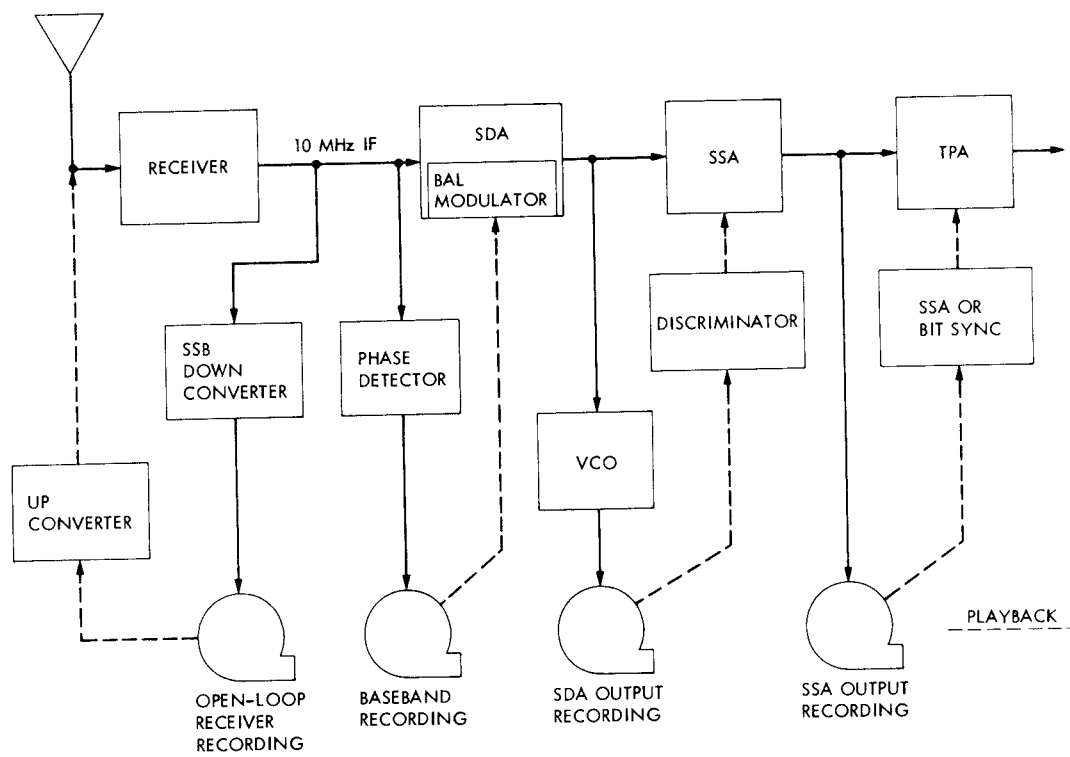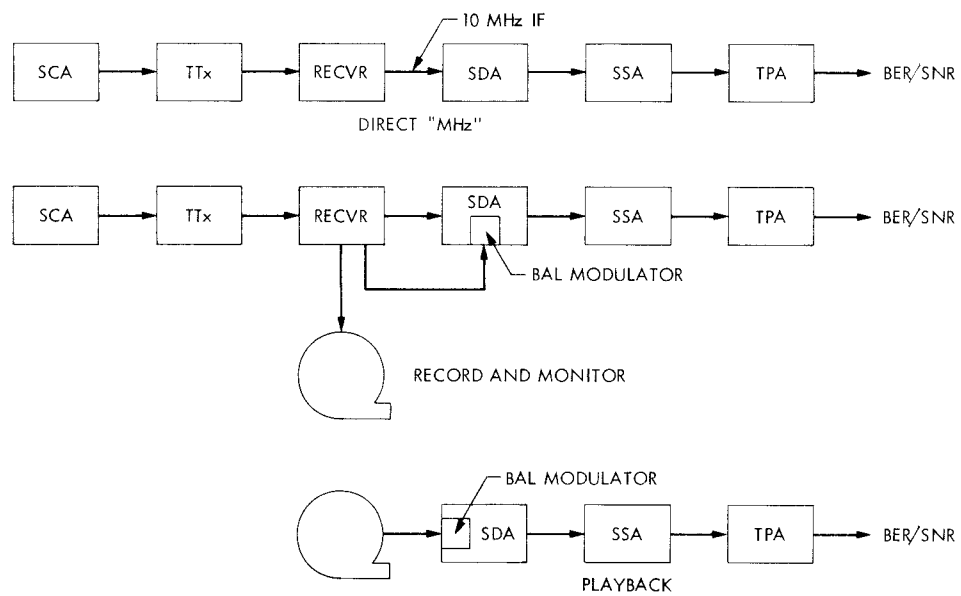
**Fig. 1. Analog recording techniques**

**Fig. 2. Baseband recording and playback test configurations**